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Monitoring the Coastal Environment; Part III: Geophysical and Research Methods

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ABSTRACT

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Acoustic and electromagnetic geophysical methods are widely used in coastal studies for determining water depth, identifying bottom sediment type and surficial features, locating man-made objects and hazards, and studying sub-bottom geology and structure. Acoustic methods are broadly divided into categories: 1. high-frequency systems such as echo-sounders whose main purpose is to determine water depth (minimal seafloor penetration); 2. lower-frequency systems with the ability to penetrate bottom sediments.

Coastal hydrographic surveys must be conducted by qualified personnel with meticulous quality-control procedures. The maximum practicable achievable accuracy for coastal surveys using echo sounders is about ± 0.5 ft (0.15 m).

High-resolution seismic surveys are used for engineering and for beach fill studies. The thinnest bed or layer that can be detected is about $\lambda/4$, where λ is the wavelength of the acoustic source.

ADDITIONAL INDEX WORDS: *Depth sounding, sub-bottom profiling, side-scan sonar, ground penetrating radar, hydrogrphic surveying, acoustic impedences, high-resolution seismic.*

INTRODUCTION

This is the third paper in a series of four describing practical procedures for monitoring coastal processes and collecting geologic, sedimentary, hydrographic, and hydraulic data in the coastal zone. This paper concentrates on geophysical survey methods and analyses. We emphasize basic procedures and descriptions of some of the underlying geophysical relationships.

Some geophysical methods, such as subbottom profiler data recorded on analog paper records, may be considered old-fashioned, but they are still widely used for many engineering and geological studies. The state-of-the-art is changing rapidly, and modern digital systems are proving to be remarkably powerful tools. However, for many studies, simple techniques are adequate and many researchers and contractors are still using traditional analog systems.

BACKGROUND

Geophysical survey techniques, involving the use of acoustic transmission, receiving, and measuring instruments and high quality positioning systems on survey boats, are widely used for gathering subsurface geological and geotechnical data in coastal environments. Other methods, such as magnetic, gravity, and electrical resistivity, are used in specialized engineering applications (GRIFFITHS and KING, 1981), but are not common in reconnaissance coastal studies and therefore will not be discussed in this paper. *Geophysics* is defined as the "study of the earth by quantitative physical methods" (BATES and JACKSON, 1984). Geophysical methods are a form of remote sensing in that a researcher uses a tool to remotely image the seafloor or the strata below. The result is a depiction of the subsurface geology, a model based on varying acoustic impedances of air, water, sediment, and rock. The model, which must be interpreted, is based on numerous assumptions, and the user must always remember that the real earth may be very different than the model printed on paper or displayed on his monitor. This warning notwithstanding, geophysical (particularly acoustic) methods have proven to be extremely powerful tools in numerous coastal applications, including:

- Determining water depth (hydrographic surveys)
- Imaging the sea bottom to identify surficial sediments, measure bottom features such as ripples, and locate man-made structures and debris
- Measuring the thickness of strata to locate suitable quantities of sand for beach renourishment
- Mapping gas pockets, rock outcrops, and other geological hazards
- Identifying coral and other biologically sensitive areas

Echo sounders or depth-sounders,[1] side-scan sonar, and

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[1] Often called Fathometer, although this is a Raytheon trade name and not a generic term.

Table 1. *Summary of acoustic survey systems.*

Acoustic System	Frequency (kHz)	Purpose
Sea floor and water column		
Echo sounder (single beam)	12–200	Measure water depth for bathymetric mapping
Echo sounder (multi-beam)	75–455	Map sea floor topography and structures
Water column bubble detector (tuned transducer)	3–12	Detect bubble clusters, fish, flora, debris in water column
Side-scan sonar	38–455	Map sea floor topography, sediment type, texture, outcrops, man-made debris, structures
Subbottom profilers		
Tuned transducers	3.5–7.0	High-resolution subbottom penetration
Electromechanical:		
Acoustipulse®	0.8–5.0	Bottom penetration to ~30 m
Uniboom®	0.4–14	15–30 cm resolution with 30–60 m penetration
Bubble Pulser	~0.4	Similar to Uniboom®
Sparker:		
Standard	50–5,000 Hz	Use in salt water (minimum 20‰), penetration to 1,000 m
Optically stacked	(same)	Improved horizontal resolution
Fast-firing 4 KJ & 10 KJ	(same)	Improved horizontal and vertical resolution
De-bubbled, de-reverberated	(same)	Superior resolution, gas-charged sediment detection
Multichannel digital	(same)	Computer processing to improve resolution, reduce noise

From SIECK and SELF (1977), EG&G®, Datasonics®, Reson®, and other company literature

subbottom profilers are three classes of equipment used to collect geophysical data in marine exploration programs. All three are acoustic systems that initiate the propagation of sound pulses in the water and measure the lapsed time between the initiation of the pulse and the arrival of return signals reflected from various target features on or beneath the seafloor. Single-beam acoustic depth-sounders are used for bathymetric surveys. Multi-beam echo sounders are improvements on the traditional single beam systems, allowing very detailed imaging of underwater structures and topography. Side-scan sonar provides an image of the aerial distribution of sediment, surface bed forms, and large features such as shoals and channels. It can thus be helpful in mapping directions of sediment transport. Subbottom profilers, as the name implies, are used to examine the stratigraphy below the seafloor. Table 1 lists frequencies of common acoustic geophysical tools.

Ground-penetrating radar (GPR) uses electromagnetic energy to image subbottom sediments. Radiowave energy is transmitted through the sediment and reflects from materials as a function of variations in dielectric constants and electrical resistivity. The main limitation of GPR is that it must be used in freshwater environments or in barrier locations where salinity is very low.

A single geophysical method rarely provides enough information about subsurface conditions to be used without sediment samples or additional data from other geophysical methods. Each geophysical technique typically responds to different physical characteristics of earth materials, and correlation of data from several methods provides the most meaningful results. *All geophysical methods rely heavily on experienced operators and analysts.* Inexperienced users should seek help both in contracting for surveys and in interpreting records.

HYDROGRAPHIC (WATER DEPTH MEASUREMENT) SYSTEMS[2]

Importance of Surveys

Hydrographic charting has always been of critical concern for navigation. As foreign trade becomes increasingly important in the world economy, many harbors are being improved to handle larger deep-draft merchant vessels. As a result, many coastal inlets are being deepened to accommodate larger vessels, and the measurement of water depth remains vital to navigation safety. Bathymetric surveys are also required for most coastal geology and geomorphology studies. Water depths are measured by both direct contact procedures and by indirect (acoustic or electromagnetic) methods, as described in the following paragraphs.

Direct Elevation Measurements (Lead Lines and Sounding Poles)

Before the mid-1930's, most hydrographic data was collected with lead lines or sounding disks, a labor-intensive, slow procedure (SHALOWITZ, 1964). In the Great Lakes, soundings were sometimes made through winter ice to eliminate the problems of seiching and other water-level oscillations. Lead lines and sounding poles are still used in shallow locations where electronic echo sounders might produce erroneous results, such as near rock structures or bulkheads that cause strong side echoes or in areas of dense vegetation. A sounding pole is the most accurate hydrographic measuring device in shallow water. Procedures for using lead lines and poles in shallow water are described in HEADQUARTERS, U.S. ARMY CORPS OF ENGINEERS (USACE) (1994); equipment specifi-

[2] Lead reference for this section is the Corps of Engineers' Engineer Manual "Hydrographic Surveying" (HEADQUARTERS, USACE 1994).

cations are listed in the National Oceanic and Atmospheric Administration (NOAA) *Hydrographic Manual* (UMBACH, 1976). Note that sleds, commonly used to collect shore-parallel profiles, are a form of sounding pole. Beach profiling concepts and equipment are discussed in Paper 4 of this series (GORMAN, MORANG, and LARSON, 1997, *this edition*).

Acoustic Depth-Sounders

The development of acoustic, electronic survey instruments after World War I revolutionized river, lake, and offshore surveying because large areas could be covered rapidly from motorized vessels, allowing a survey to be completed before storm waves or currents might alter the seafloor. Acoustic depth-sounders measure the elapsed time an acoustic pulse takes to travel from a generating transducer to the seafloor and back. If the velocity of sound in water is known, the travel time of the reflected wave can be measured and converted into distance:

$$d = \frac{v \cdot t}{2} + k + d_r \tag{1}$$

where:

- d = depth from reference water surface
- v = average velocity of sound in the water column
- t = measured elapsed time from transducer to bottom and back to transducer
- k = system index constant
- d_r = distance from reference water surface to transducer (draft)

Values of v, t, and d_r cannot be exactly determined during the echo sounding process, and k must be derived from periodic calibrations of the equipment. The calibration procedure is also not precise. The measured time t depends upon the reflectivity of the bottom as well as the signal processing methods used to detect a valid return. The shape or sharpness of the return pulse plays a major role in the accuracy and detection capabilities of depth measurement.

Survey Classes and Accuracy Criteria

Hydrographic surveying requires the application of two technical disciplines: horizontal positioning and water depth measurement. The quality, and cost, of the final results is directly related to the accuracy and precision of both elements. For shallow coastal and inland water work, the Corps of Engineers has standards for three classes of hydrographic surveys:

- Class 1—Contract payment surveys—high accuracy
- Class 2—Project condition surveys—medium accuracy
- Class 3—Reconnaissance surveys—low accuracy

Table 2 lists the maximum allowable errors for each class. Although the requirements of geologic site surveys may not be the same as those of Corps of Engineers hydrographic surveys, the accuracy standards are useful criteria when specifying quality control requirements in contractual documents. The frequency of calibration is the major distinguishing factor between the classes of survey and directly affects the accuracy and adequacy of the final data. Calibrations are time-consuming and reduce actual data collection time. Nevertheless, this must be countered with the economic impact resulting from low quality data that may be useless or may even lead to erroneous conclusions (leading, in turn, to incorrectly designed projects and possible litigation). With the increasing use of Geographic Information Systems (GIS) for analysis and manipulation of data, high standards of accuracy are imperative. Planning and successfully implementing offshore surveys are sophisticated activities and should be carried out by personnel or contractors with experience and a record of successfully achieving the accuracies specified for the particular surveys.

Table 2. *Maximum allowable errors for hydrographic surveys.*

	Survey Classification		
Type of Error	1 Contract Payment	2 Project Condition	3 Reconnaissance
Resultant two-dimensional one-sigma RMS positional error not to exceed	3 m	6 m	100 m
Resultant vertical depth measurement one-sigma standard error not to exceed	±0.152 m (±0.5 ft)	±0.305 m (±1.0 ft)	±0.457 m (±1.5 ft)

From HEADQUARTERS, USACE (1994)

Positioning System Criteria

Table 3 depicts positioning systems which are considered suitable for each class of survey. The table presumes that the typical project is located within 40 km (25 mi) of a coastline or shoreline reference point. Surveys further offshore should conform to the standards in the NOAA *Hydrographic Manual* (UMBACH, 1976).

Causes of Survey Errors

Errors in acoustic water depth determination are caused by the following physical and mechanical factors:

Velocity of Sound in Water

The velocity, V, in near-surface water ranges from 1,400 to 1,525 m/sec (4,600 to 5,000 ft/sec), but varies with water density, which is a function of temperature, salinity, and suspended solids (HEADQUARTERS, USACE, 1994; p. 8–14). An average of 1,500 m/sec is assumed for many surveys in salt water. In estuaries or river mouths, water density can vary greatly within the water column, and in areas subject to freshwater runoff, it is *not* valid to assume that an average V can be used over the entire area and for all water depths. For example, a 10‰ (parts per thousand) salinity change can change the velocity by 12 m/sec (40 ft/sec), or 0.12 m in 15 m (0.4 ft in 50 ft). Therefore, for highest precision surveys, the acoustic velocity must be calibrated onsite frequently using a bar check.

Table 3. *Allowable horizontal positioning system criteria.*

Positioning System	Estimated Positional Accuracy (meters, RMS[1])	Allowable for Survey Class 1	2	3
Visual Range Intersection	3 to 20	No	No	Yes
Sextant Angle Resection	2 to 10	No	Yes	Yes
Transit/Theodolite Angle Intersection	1 to 5	Yes	Yes	Yes
Range Azimuth Intersection	0.5 to 3	Yes	Yes	Yes
Tag Line (Static Measurements from Bank)				
<457 m (1,500 ft) from baseline	0.3 to 1	Yes	Yes	Yes
>457 m (1,500 ft) but <914 m (3,000 ft)	1 to 5	No	Yes	Yes
>914 m (3,000 ft) from baseline	5 to 50+	No	No	Yes
Tag Line (Dynamic)				
<305 m (1,000 ft) from baseline	1 to 3	Yes	Yes	Yes
>305 m (1,000 ft) but <610 m (2,000 ft)	3 to 6	No	Yes	Yes
>610 m (2,000 ft) from baseline	6 to 50+	No	No	Yes
Tag Line (Baseline Boat)	5 to 50+	No	No	Yes
High-Frequency EPS[2] (Microwave or UHF)	1 to 4	Yes	Yes	Yes
Medium-Frequency EPS	3 to 10	No	Yes	Yes
Low-Frequency EPS (Loran)	50 to 2,000	No	No	Yes
Satellite Positioning:				
Doppler	100 to 300	No	No	No
STARFIX	5	No	Yes	Yes
NAVSTAR GPS[3]:				
Absolute Point Positioning (No SA[4])	15	No	No	Yes
Absolute Point Positioning (w/SA)	50 to 100	No	No	Yes
Differential Pseudo Ranging	2 to 5	Yes	Yes	Yes
Differential Kinematic (future)	0.1 to 1.0	Yes	Yes	Yes

[1]Root Mean Square
[2]Electronic Positioning System
[3]Global Positioning System
[4]Selective Availability
From HEADQUARTERS, USACE (1994)

Boat-Specific Corrections

As the survey progresses, the vessel's draft changes as fuel and water are used or as loads (equipment and personnel) are exchanged. Depth checks should be performed several times per day to calibrate the echo sounders.

Survey Vessel Location with Respect to Known Datums

An echo sounder on a boat simply measures the depth of the water as the boat moves over the water column. However, the boat is a platform that moves vertically depending on oceanographic conditions such as tides and surges. To obtain water depths that are referenced to a known datum, echo sounder data must be adjusted in one of two ways. First, tides can be measured at a nearby station and the echo sounder data adjusted accordingly. Second, the vertical position of the boat can be constantly surveyed with respect to a known land datum and these values added to or subtracted from the recorded water depths. For a Class 1 survey, either method of data correction requires meticulous attention to quality control.

With the first procedure, the water surface is normally referenced to an on-shore reference benchmark or gauge. The most common source of error is the assumed stability of the water surface between the on-shore gauge and the survey vessel. In coastal projects subject to tides, ebb/flood flow, or riverine discharge, surface gradients between the gauge and the vessel can amount to more than 0.6 m, and depth data must be corrected. For this reason, tide staffs are normally established in the immediate project area (*i.e.,* it is not valid to observe the tide on an intracoastal waterway for an offshore survey). To reduce the effect of wind setups, surveys should be conducted under low wind conditions (less than 15 knots). Table 4 lists requirements for water level measurements based on class of survey.

Waves

As the survey boat pitches up and down, the seafloor is recorded as a wavey surface. To obtain the true seafloor

Table 4. *Tide and water level measurement criteria.*

Criteria	Minimum Standard per Survey Class 1	2	3
Gauge/Tide Staff Location[1]	On-site	On-site	Near-site
Tidal Zoning Requirements	Determine on case-by-case basis		Not required
Gauge Reading Frequency	As needed for 0.1 ft (0.03 m) surface change		
Leveling frequency—Gauge to Benchmarks per Project[2]	Start and finish of project		Project start only
Start/Finish Difference in Gauge Reference Elevation	0.05 ft (0.015 m)	0.1 ft (0.03 m)	----------
Staff Marking Intervals	0.1 ft (0.03 m)		
Least Count of Readings	0.1 ft (0.03 m)		
Stilling Wells Required if Sea States Exceed	0.5 ft (0.15 m)	1.0 ft (0.31 m)	2.0 ft (0.61 m)

[1]An *on site gauge* is defined as a being in a location relative to the project area such that *not more* than the following surface gradient exists between gauge and vessel:
Class 1: 0.1 ft (0.03 m)
Class 2: 0.3 ft (0.09 m)
Class 3: 0.8 ft (0.24 m)
Tidal or surface gradient zoning is required if these criteria cannot be met
[2]FGCC 3rd order levels—2 benchmarks required
From HEADQUARTERS, USACE (1994)

Table 5. *Estimated depth measurement accuracy*

Error Source	Estimated Standard Error per Condition (± meters)			
	Ideal	Average <20 ft (6 m)	Average >20 ft (6 m)	Coastal
Measurement System	0.015	0.015	0.03	0.06
System Calibration	0.011	0.03	0.06	0.09
Resolution	0.03	0.03	0.03	0.06
Draft/Index		0.015	0.03	0.06
Reference datum:				
Vertical	0.015	0.015	0.015	0.015
Tide/Stage	0.006	0.06	0.06	0.15
Platform Stability	0.015	0.06	0.09	0.3
Velocity		0.03	0.03	0.06
Density/Sensitivity	0.015	0.015	0.3	0.15
Resultant MSE	±0.046	±0.09	±0.15	±0.40

From Headquarters, USACE (1994) (converted to metric units)

depth for the highest quality surveys, transducers and receivers are sometimes installed on heave-compensating mounts. These allow the boat to move vertically while the instruments remain fixed. Electronic heave compensation instruments are available that filter the wave signal as the survey progresses. Both methods are effective.

Estimated Depth Measurement Accuracy

Even with the best efforts at equipment calibration and data processing, the maximum practicable achievable accuracy for coastal surveys using echo sounders is about ± 0.5 ft (0.15 m) (Headquarters, USACE, 1994, pp. 9–29). Under average river and harbor project conditions, the estimated accuracy of an individual sounding falls between ± 0.2 and ± 0.5 ft (0.61–0.15 m). Table 5 lists quantitative estimates of depth measurements under different survey conditions. The resultant depth accuracy of an overall survey is highly variable, regardless of the class specified for the project. For example, a survey intended to be Class 1 conducted 10 km offshore with poor tidal modeling may actually be accurate only to Class 3 criteria (± 1.5 ft). Thus, estimated resultant error must be evaluated on a project-by-project basis.

Examples

Figure 1 is an example of analog echo sounder data from offshore Palm Beach County, Florida. This data was recorded on the paper charts at a range of 0 to 110 ft, so to read the depths, a user should use the 0 to 55-ft printed scale and multiply by 2. For example, the top of the prominent lump near Fix 299 has a depth of about 52 ft. This data was collected a kilometer offshore without any tidal modeling nor with establishment of offshore tide gauges. Therefore, accuracy is Class 3 or worse, and we can assume, at best, an accuracy of ± 2 ft. This means that we can only state that the lump is between 50 and 54 ft deep. Because sea conditions were mild, wave noise is a minor problem in these records. In any case, here the inaccuracies caused by the lack of tidal modeling are much greater than inaccuracies caused by wave noise.

Figure 2 is contoured digital bathymetric data from the Yaquina entrance, Oregon, collected with a single-beam survey system. This is a complicated terrain with exposed rock reefs. Line spacing was close and the survey was conducted under tight specifications, equivalent to Class 1. Running high quality surveys is difficult in the North Pacific because of frequent stormy weather and high seas.

MULTI-BEAM ECHO SOUNDERS

Recently, multi-beam echo sounders, capable of generating remarkably detailed images of the seafloor or of submerged structures, have been marketed. The shallow water multi-beam systems are compact, high-frequency, high-resolution units that produce multiple beams from a single transducer head using arrays of miniature transducers and electronic signal control (Figure 3). Examples include the Sea Beam 1000® (75 kHz), Simrad EM 950® (95 Khz), Krupp-Atlas Fansweep® (200 kHz), and the Reson SeaBat® (455 kHz). These systems are now practical for small boat operations as a result of the simultaneous development of several critical technologies: rapid-response heave-roll-pitch sensors, precise positioning (in particular, differential global positioning systems (DGPS)), computerized integration of navigation with the sensor systems, and computerized data management and display. An important note regarding multi-beam systems: the amount of data collected at any site is dramatically greater than the amount collected with conventional survey methods. Much more computer software and hardware is needed to process these data, and many agencies are not yet equipped to manage it. Archiving these files will become an ever-greater problem.

Figure 4, an example of processed multi-beam data from the SeaBat 9001, shows the north side of the Yaquina north jetty, off Newport, Oregon (see Figure 2 for location). The bumpy texture of the jetty is armor stone. The portion of the jetty imaged by the SeaBat extended from −1.5 m mllw down to about −5 or −6 m. This image is composed of 145,000 data points. To monitor the condition of the jetty above the water line, Portland District used low level aerial photography, plotting and comparing the location of individual armor stones with Geographic Information System (GIS) software.

Thanks to rapidly-improving processing and data-recording capabilities, the state of science is constantly improving in this field. Users need to contact equipment manufacturers and review *Journal of Coastal Research, Journal of Geophysical Research, Marine Technical Society Journal, International Underwater Systems Design,* and trade journals for more information.

Many ships and most submersibles are now equipped with ahead-look sonars (ALS). This, too, is a new technology greatly dependent on sophisticated signal processing and transducer design. Ahead-look sonar mounted on small remote-operated vehicles has been used to inspect underwater portions of coastal structures in environments where a manned survey boat cannot approach the structure safely. Loggins

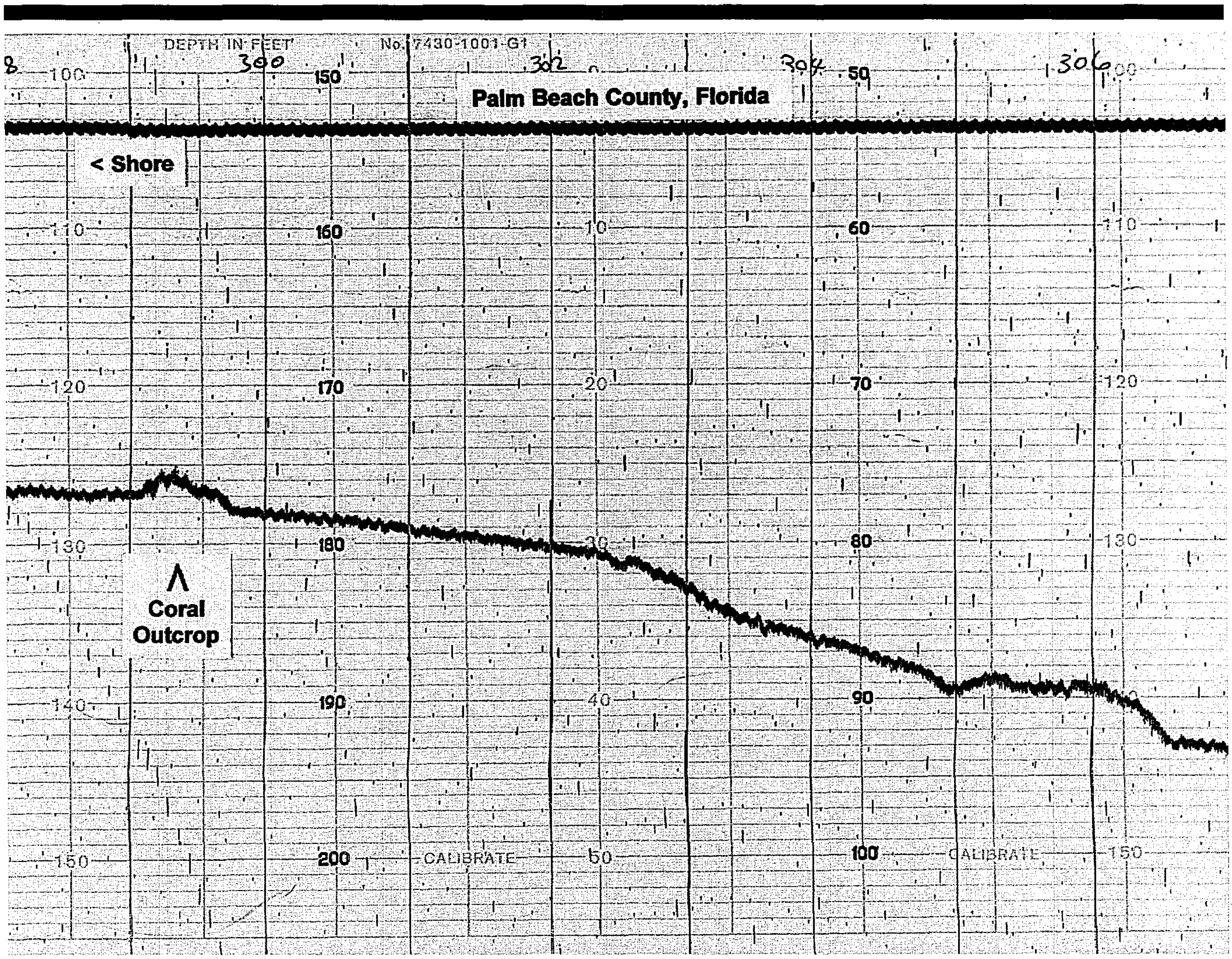

Figure 1. Analog echo sounder record from offshore Palm Beach County, Florida (Coastal Engineering Research Center (CERC) data). Shore is to the left. The lump near Fix 299 is a coral outcrop.

(1995) lists frequencies, resolution, and other characteristics of various ALS systems.

HIGH-RESOLUTION SUBBOTTOM PROFILING

Definitions

High-resolution geophysics refers to the use of acoustic sources, sound receivers, signal processing equipment, and graphic displays to define water depth and provide cross-sectional views of the sediments and strata below the seafloor (SIECK and SELF, 1977) (Figure 5). *Signal* denotes any event on a seismic record from which information can be obtained (SHERIFF and GELDART, 1982). Everything else in the record is *noise.* The principles of subbottom seismic profiling are fundamentally the same as those of acoustic depth-sounding, but subbottom acoustic transmitters and receivers employ lower frequency, higher power signals to penetrate the seafloor (Table 1). "High-resolution" generally means that the surveys are intended for engineering purposes or for identifying strata and structures in the uppermost 50 or 60 m of the sediment column[3]. Typical applications include reconnaissance geological surveys, foundation studies for offshore platforms, hazards surveys to locate buried debris and gas pockets, and surveys to identify mineral resources (*e.g.,* sand for beach renourishment).

Principles

Transmission of acoustic waves through sediment and rock depends upon earth material properties such as density, composition, and water and gas content (SHERIFF, 1980). The most common model of acoustic waves in the earth is of a simple harmonic disturbance passing through an elastic me-

[3] As a matter of confusion, seismic surveys using low frequency, very high power sources for deep penetration, such as oil exploration, are not called "low resolution."

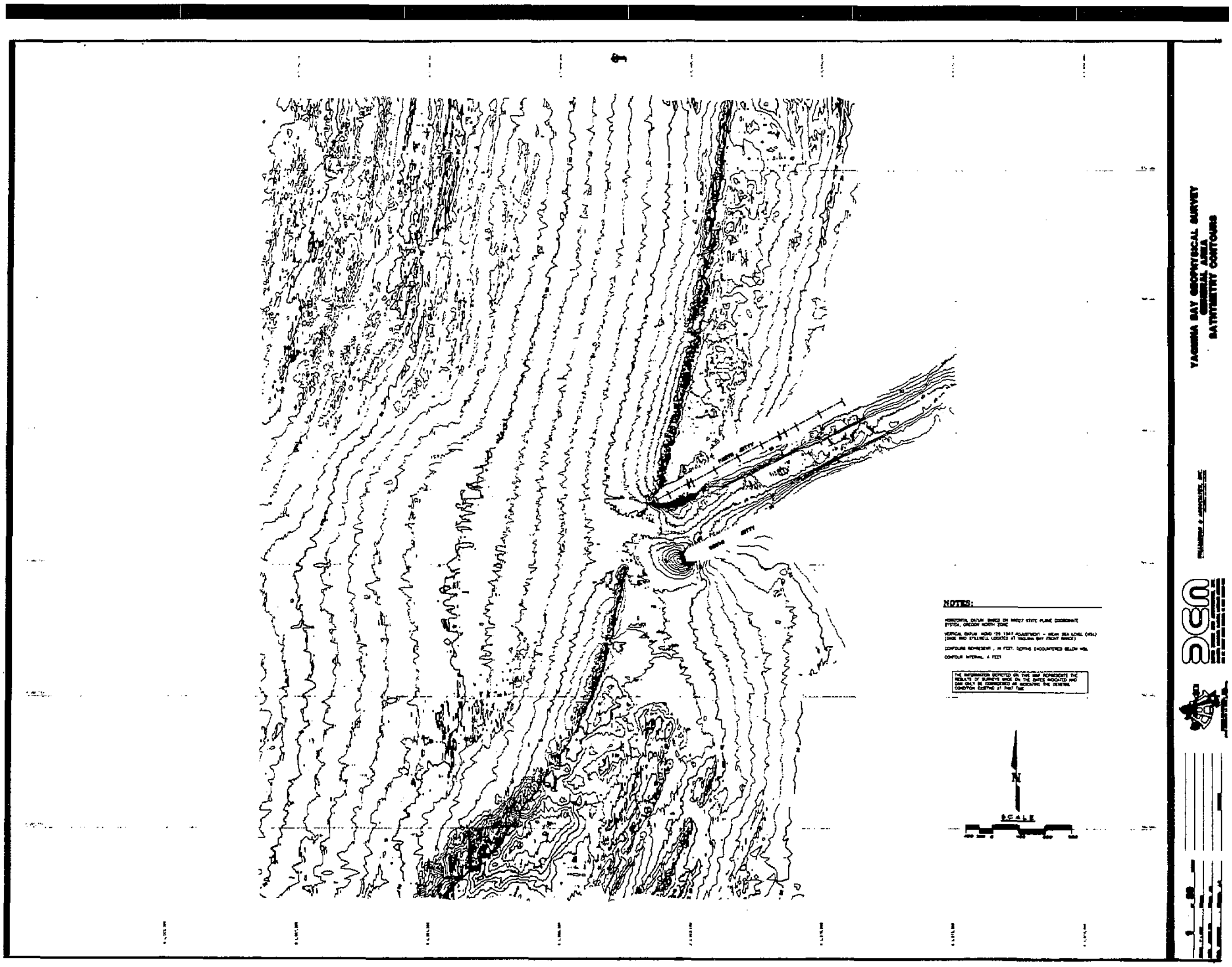

Figure 2. Contoured bathymetry off Yaquina Entrance, Oregon, collected with a single-beam acoustic system with close line spacing and tight specifications (from HUGHES *et al.* (1995)).

dia (similar to the treatment used in optics or ocean waves) such that:

$$T = \frac{\lambda}{V}$$

$$\nu = \frac{1}{T} = \frac{V}{\lambda}$$

$$V = \nu\lambda \qquad (2)$$

where:

T = period of the acoustic wave
ν = frequency
λ = wavelength
V = speed of the wave "disturbance"

When a wave encounters an abrupt change in elastic properties, part of the energy is *reflected* while the balance is *refracted* into the other medium. The proportion of energy that is reflected and refracted is described by Snell's Law (SHERIFF and GELDART, 1982):

$$\frac{\sin \Theta_1}{V_1} = \frac{\sin \Theta_2}{V_2} = p \qquad (3)$$

where:

V_1 = velocity of sound in the upper media
V_2 = velocity of sound in the lower media
Θ_1 = angle of incidence
Θ_2 = angle of refraction

The quantity p is called the *raypath parameter.* The above relationship assumes a planar surface and, therefore, specular reflections. If the surface is irregular and has bumps of height d, reflected waves from the bumps reach the receiver before the waves from the rest of the surface by a distance $2d$. These can be neglected where $2d/\lambda < 1/4$ (the "Rayleigh criterion"), *i.e.,* when $d < \lambda/8$ (SHERIFF and GELDART, 1982).

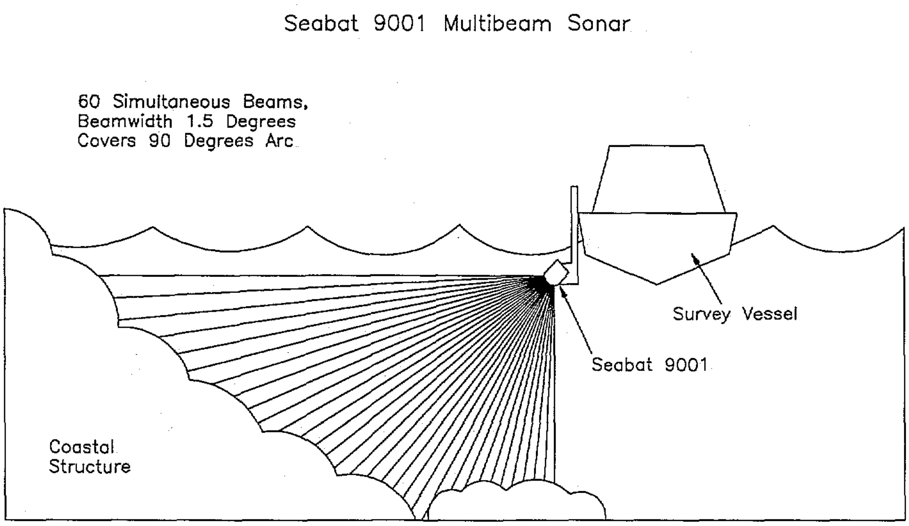

Figure 3. Beam pattern of the SeaBat 9001, showing its ability to image submerged portions of breakwaters.

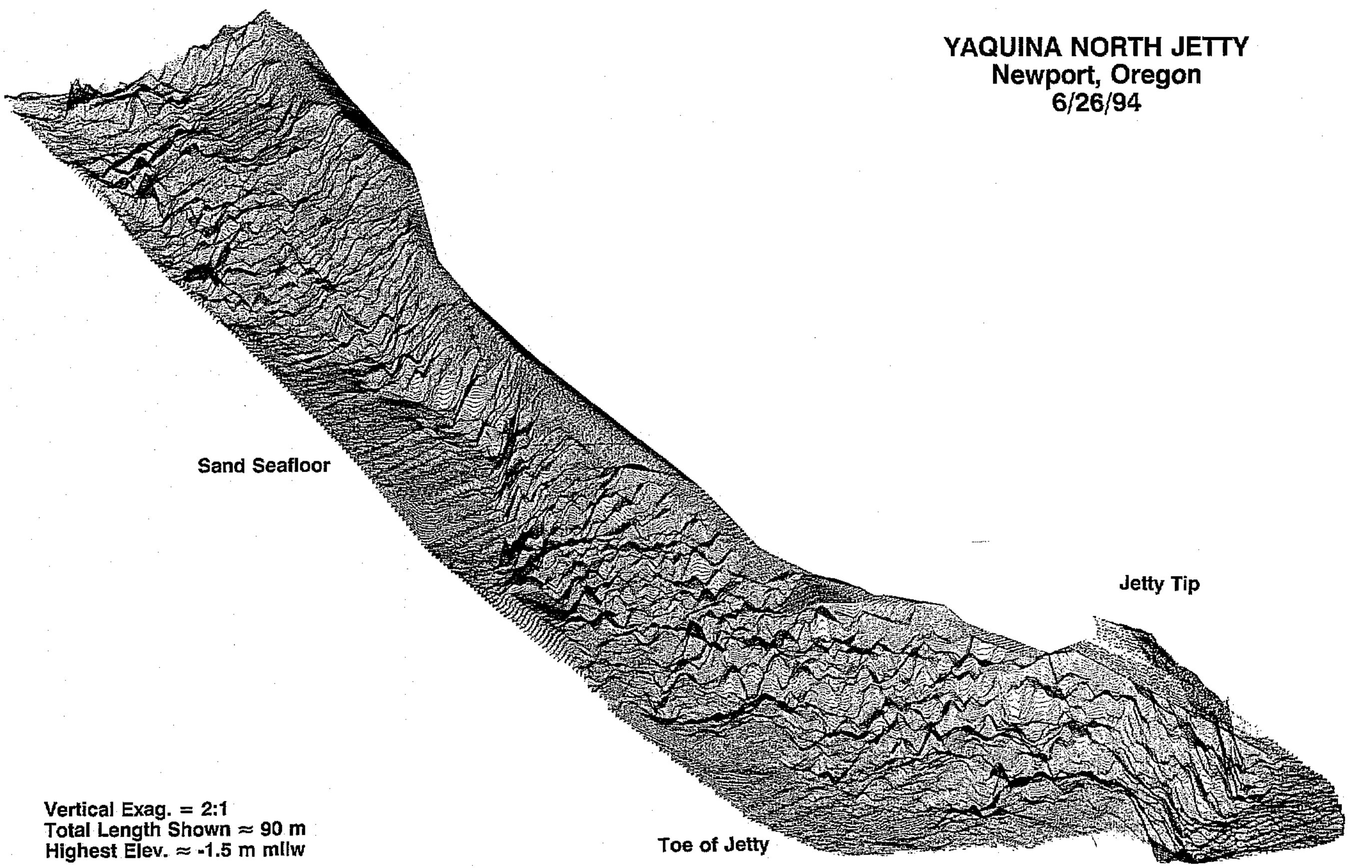

Figure 4. Processed SeaBat 9001 image of Yaquina North jetty. Image shows about 90 m of the seaward (north) side of the rubblemound structure from a depth of −1.5 m mllw down to the seafloor.

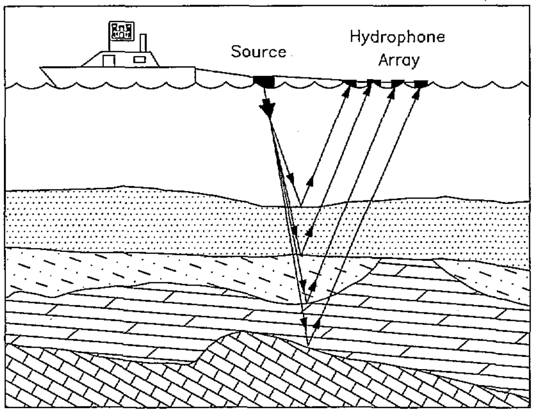

Figure 5. Subbottom seismic surveying from a small boat.

This tells us that there is a practical limit to the size of features that can be detected on a surface which depends on the frequency (and hence the wavelength), of the acoustic signal source. For example, if a Bubble Pulser source is used with a dominant frequency of 400 Hz (Table 1), the wavelength in sandstone, assuming a velocity of 2,000 m/s, is equal to 5 m. Therefore, an irregularity d would not be detected if it were less than about ⅛ × 5 or 0.6 m high.

The strength of a reflected signal, and hence the ability to detect an interface, depends upon the partitioning of energy as the signal is partly reflected and partly refracted at the material interface. Mathematical relationships known as Zoeppritz' equations (detailed in SHERIFF and GELDART (1982)) describe this partitioning. The fractions of energy reflected and transmitted are given by E_R and E_T, where $E_R + E_T = 1.0$. E_R is calculated from:

$$E_R = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2 = R^2 \tag{4}$$

where:

$Z_i = V \times \rho$ (velocity times density) (*i.e., acoustic impedance*)
R = *reflection coefficient* (also known as the *reflectivity*)

Table 6 lists densities of common materials encountered in seismic prospecting. It shows that as the difference in impedance between the two materials increases, R increases, thus resulting in more reflected energy. For example, a hard seafloor produces a stronger return than a soft seafloor. For most interfaces within the earth, impedance contrasts are small and typically less than 1 percent of the energy is reflected. This is why sophisticated data processing and noise-reduction procedures are needed to reveal strata deep within the earth. Because the seafloor, the sea surface, and the base of the weathering layer are relatively strong reflectors, they are responsible for most of the multiple reflectors that often obscure portions of subbottom returns.

Lack of signal penetration is caused by many conditions. Coarse sand and gravel, glacial till, and highly organic sediments are often difficult to penetrate with conventional subbottom profilers, resulting in records with data gaps. The lack of penetration itself is a diagnostic tool. For example, gassy sediments cause serious signal degradation and gaps in records (Figure 6). Often, little useful subbottom data can be collected in estuaries and river mouths because they contain so much organic material. For example, much of Chesapeake Bay is almost opaque to high-resolution seismic imaging. In these conditions, cores may be necessary to fill in the missing geological information. Digital signal processing of multichannel data can sometimes extract useful data despite poor signal penetration or noise. However, signal processing is not magic and there are limits to what it can achieve in difficult environments.

Several kinds of spurious signals (*i.e.,* noise) cause difficulties in interpreting analog seismic records[4]:

- Direct arrivals—signal received directly from the sound source
- Multiple reflections—repeated echoes from a strong reflector, usually the seafloor
- Water surface reflection
- Side echoes—reflections from irregular bottom or hard objects such as man-made structures
- Single point reflections—reflected energy radiated from small point objects such as rock pinnacles or pipelines

[4] From booklet prepared by EG&G Corporation, Waltham, Massachusetts, 1977.

Table 6. *Energy reflected at interface between two media.*

Interface	First Medium		Second Medium				
	Velocity[1]	Density[2]	Velocity	Density	Z_1/Z_2	R	E_R
"Soft" ocean bottom	1.5	1.0	1.5	2.0	0.50	0.33	0.11
"Hard" ocean bottom	1.5	1.0	3.0	2.5	0.20	0.67	0.44
Ocean bottom with gas sand	1.5	1.0	2.2	1.8	0.38	0.45	0.20
Surface of ocean	1.5	1.0	0.36	0.0012	3,800	−0.9994	0.9988
Base of weathering	0.5	1.5	2.0	2.0	0.19	0.68	0.47
Shallow interface	2.1	2.4	2.3	2.4	0.93	0.045	0.0021
Sandstone on limestone	2.0	2.4	3.0	2.4	0.67	0.2	0.04

[1]km/s
[2]g/cm³
Condensed from SHERIFF and GELDART (1982)

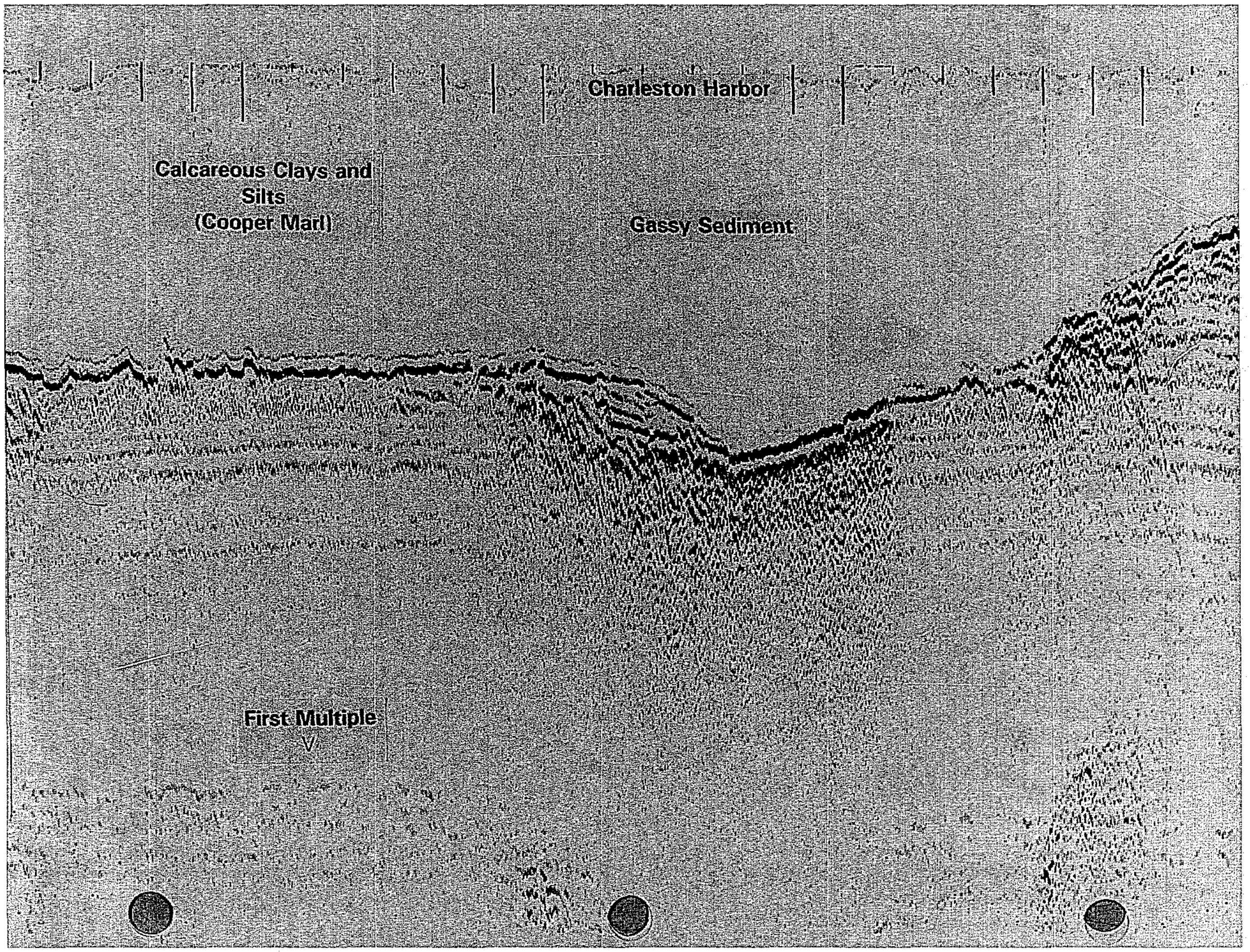

Figure 6. Subbottom profiler record from Charleston Harbor showing gassy sediment. Data collected with a digitally-recording boomer system.

Resolution

The two most important parameters of a subbottom seismic reflection system are its vertical resolution and penetration. As the dominant frequency of the output signal increases, the resolution, or the ability to differentiate closely spaced reflectors, becomes more refined. Unfortunately, raising the frequency of the acoustic pulses increases attenuation of the signal and consequently decreases the effective sediment penetration. Thus, it is a common practice to use two seismic reflection systems simultaneously during a survey; one of high-resolution capabilities and the other capable of greater penetration.

The thinnest bed or layer that can be detected is about $\lambda/4$ (SHERIFF, 1977). Using the example of a 400 Hz signal in sandstone with $\lambda = 5$ m, layers as thin as 1.25 m should be detectable (providing, of course, that there are sufficient acoustic impedances to produce measurable reflections). If a 3.5 kHz profiler is used, the wavelength in sandstone is much smaller, about 0.6 m, and layers about 0.15 m thick can be detected.

During the 1980's, improvements in data acquisition and signal processing made it possible for scientists to detect thinner and thinner layers using high-frequency systems while still achieving reasonable penetration, even in sands or other difficult materials. For example, BERNÉ, AUFFRET, and WALKER (1988) were able to image the internal structure of sandwaves off Normandy, France, using a 2.5 kHz subbottom profiler.

Interpretation Pitfalls

Acoustic characteristics are related to lithology so that seismic reflection profiles can be considered analogous to a geological cross section of the subbottom material. However, because of subtle changes in acoustic impedance, reflections can appear on the record where there are only minor differences in the lithologies penetrated. Also, significant lithologic dif-

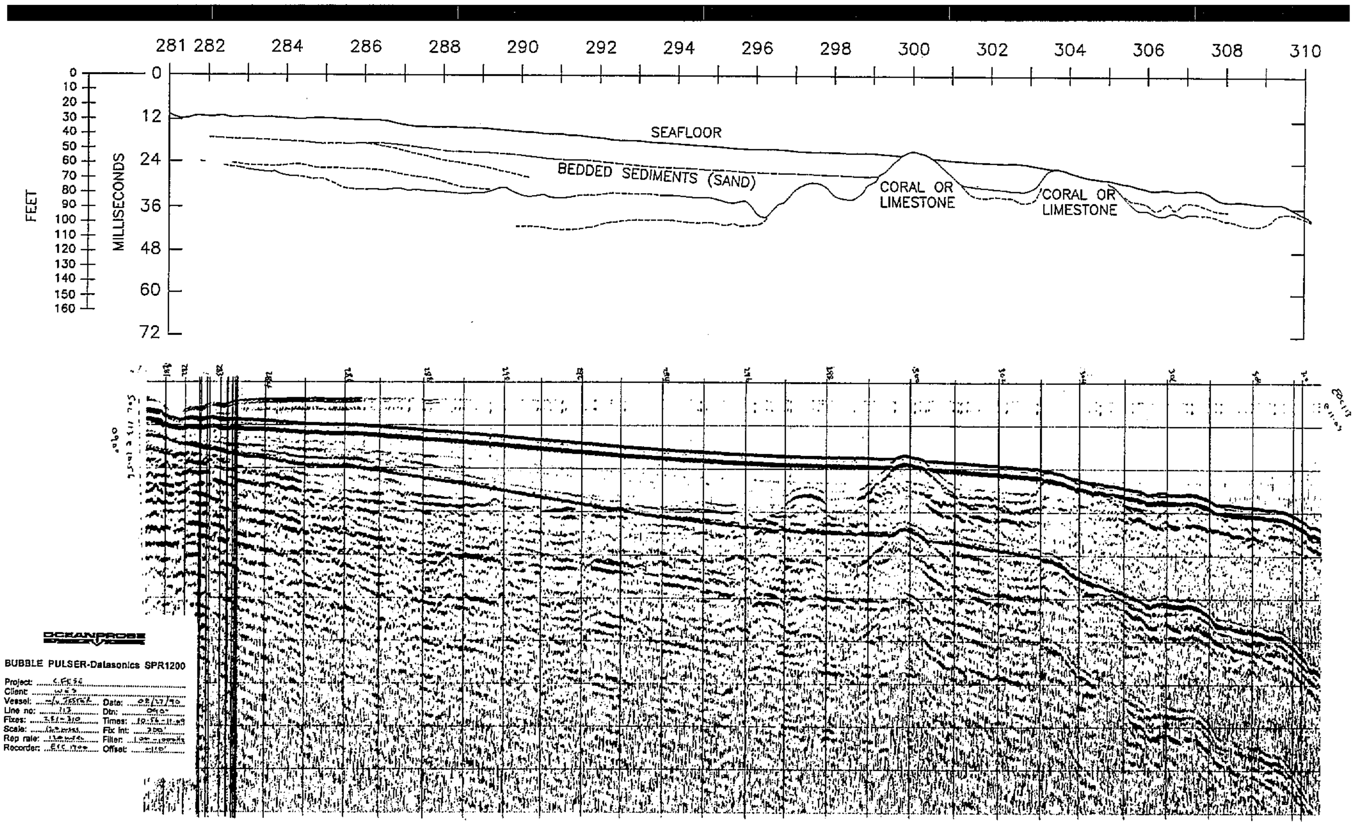

Figure 7. Analog Bubble Pulser record from off Palm Beach County, Florida, showing coral outcrops and sand basins.

ferences may go unrecorded due to similarity of acoustic impedance across interfaces, minimal thickness of the units, or masking by gas (SHERIFF, 1980). As SHERIFF (1977) has written, "Modern seismic sections often bear such striking resemblance to stratigraphic cross sections that they invite direct interpretation by people who do not appreciate geophysical limitations . . . Because most reflections are interference composites, there is no one-to-one correspondence between seismic events and interferences in the earth." The user of geophysical data should be careful *not* to assume that, in noise-free areas of good signal penetration, every waveshape variation has a geologic meaning or represents a buried feature.

Because of the dangers of incorrectly interpreting acoustic artifacts, seismic stratigraphy should always be considered tentative until supported by direct lithologic evidence from core samples. In shallow coastal areas, it is common practice by the Corps of Engineers to use water jet probing to accompany subbottom seismic surveys. This is especially important when there is a thin veneer of sand over more resistant substrate and the actual thickness of the veneer can be measured by the probing.

Interpretation Example

Figure 7 is an example of Bubble Pulser data from offshore Palm Beach County, Florida (the same line shown in Figure 1). The vertical scale of analog seismic records is often recorded in units of milliseconds of two-way travel time. The following equation converts from milliseconds to depth:

$$D = \frac{T}{2} \times V \tag{5}$$

where:

D = depth
T = Two-way travel time
V = average speed of acoustic signal

To compute the depth scale shown in Figure 7, *V* was assumed to be 1,500 m/sec (4,900 ft/sec):

$$D\ (\mathrm{ft}) = \frac{T\ (\mathrm{msec})}{2} \times 10^{-3} \times 4{,}900\ (\mathrm{ft/sec})$$

Note that accurate sound velocity data is seldom available. Therefore, layer thickness can only be approximated.

The seafloor in Figure 7 is recorded as a heavy double line. The best way to determine the actual seafloor position is to compare a known depth location with the depth recorded on the echo sounder record; in this case, the correct seafloor depth is just below the upper thick line. The first seafloor multiple occurs at two times the water depth and displays twice the slope of the original. Around Fix 294, third and fourth multiples have been recorded. An interpreter of seismic records must be careful not to confuse multiples with genuine reflectors caused by buried structures or sediments! Unfortunately, it has become a geophysicist's truism that a multiple invariably ruins the part of the record where the most interesting data should be found.

The low bump near Fix 300 is one of the coral reefs that parallel the southeast Florida coast. The reef at Fix 304 is almost flush with the surface. Coral reefs are distinguished by their steep sides and, typically, by the lack of coherent reflectors within the masses.

From Fix 282 offshore to the first exposed reef, a shallow basin appears to be filled with relatively transparent, parallel-bedded sediments, probably sand. The greatest thickness, about 5 m (15 ft), occurs near Fix 296. A small pocket of sand has collected between the two reefs (Fixes 301 to 303). Recall that earlier we estimated the resolution of a Bubble Pulser signal would be about 1.25 m (4 ft) in sandstone. Therefore, thin layers of possibly cemented sands might not be revealed by this tool. This underscores why cores are necessary to provide additional lithologic information, especially if the purpose of the survey program is to identify sediment suitable for beachfill.

Survey Patterns

As with most other types of offshore investigations, there is no "best" way to lay out a survey grid. The survey pattern must be based on the total area to be covered, types of targets being investigated, equipment and work boat to be used, time available, weather, regulations, regional hazards (such as shipping channels), and, maybe most important, funding available for the field studies. Often, experience with the use of certain tools and their efficiency in a particular geological terrain is the best guide to laying out the tracklines. The program should be flexible and amenable to changes based on interpretation of the data as it is collected (MEISBERGER, 1990). This underscores how important it is that data be reviewed *immediately,* and not just collected and saved for future interpretation. By then it will be too late to adjust field parameters, and the records may be of little value.

It is generally most appropriate to run seismic surveys in a pattern that is perpendicular to the suspected prevailing geologic structures or surficial topography (MEISBERGER, 1990). Existing scientific literature and bathymetric maps should be consulted to help plan the surveys. Along most coasts, seismic lines are run perpendicular to the shore. For example, along southeast Florida, two or three reefs run parallel to the shore and outcrop from the seafloor (Figure 7). Between the reefs are accumulations of sand of varying thickness. Surveys run perpendicular to the shore can identify the extent of the sand accumulations and the areas of hard bottom.

If the prevailing offshore geology is not parallel to the shore, the survey lines should be adjusted to best image the terrain. For example, off Ocean City, Maryland, ridges extend from the shore in a northeast direction. In this area, FIELD (1979) ran seismic lines in a grid at an angle to the shore allowing him to run both parallel and perpendicular to the ridges (Figure 8). Off Cape May, New Jersey, MEISBERGER and WILLIAMS (1980) ran lines in a rectangular grid and collected cores at selected intersection points.

For offshore areas where little is known about the surficial geology, an alternative procedure is to run survey lines in a zigzag pattern approximately perpendicular to the coast (Figure 9).

Quantitative Analysis of Subbottom Sediments

For many years, experienced geophysicists could identify and predict some properties of subbottom sediments based on the appearance of their analog records, especially if they surveyed in an area in which they had experience. This was an imprecise art at best, and numerous attempts have been made to develop quantitative methods to analyze signal returns to predict sediment properties.

The Chirp Sonar, developed in the 1980's, was originally sold as a high-resolution, quantitative profiling system. The Chirp is a system in which a minicomputer generates a frequency-modulated pulse that is phase- and amplitude-compensated to correct for the sonar system response. This precise waveform control helps to suppress correlation noise and source ringing. When the reflected signals are received, mathematical algorithms estimate the attenuation of subbottom reflections by waveform matching with a theoretically attenuated waveform. Details of the theory and mathematics behind Chirp sonar are presented in SCHOCK, LEBLANC, and MAYER (1989), LEBLANC, PANDA, and SCHOCK (1992) and SCHOCK and LEBLANC (1992). Chirp appears to work well in unconsolidated fine sediments but less successfully in sands. Its main weakness is that the final product degrades when the mathematics cannot accommodate frequency or phase changes of the returning pulses.

Another acoustic impedance system designed to assess bottom and subbottom sediments was developed at the Waterways Experiment Station and has recently been tested successfully at a number of coastal sites (MCGEE, BALLARD, and CAULFIELD, 1995). This is an empirical technique which compensates for absorption in each layer as a function of the center frequency of a band-limited seismic trace, corrects for spherical spreading, and uses classical multi-layer reflective mathematics to compute reflection coefficients at sediment horizons. This method uses discrete frequencies and is an extension of techniques developed by CAULFIELD and YIM (1983) and CAULFIELD, CAULFIELD, and YIM (1985).

SIDE-SCAN SONAR SURVEYS

Side-Scan Sonar Theory

Side-scan sonar is a system of imaging underwater objects using high-frequency acoustic signals. Originally developed during World War II to detect enemy submarines, commercial systems designed for scientific use became available in the 1960's and since then have been extensively used by oceanographic institutions, universities, pipeline and marine construction companies, archaeologists, and treasure-hunters. Side-scan sonar has become an invaluable tool to evaluate the condition of breakwaters, bridge piers, and other underwater structures (CHRZASTOWSKI and SCHLEE (1988), CLAUSNER and POPE (1988), MORANG (1987)).

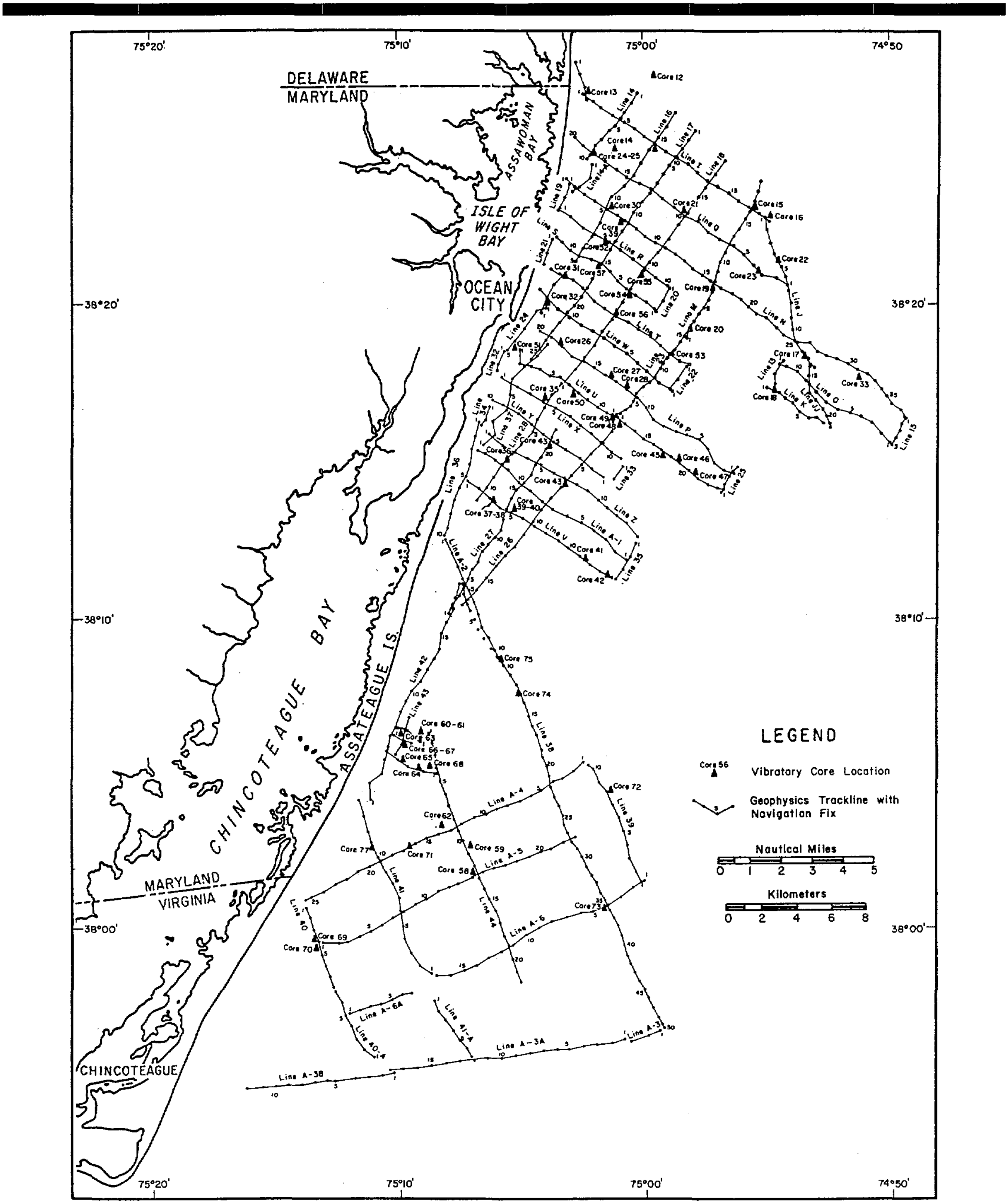

Figure 8. Rectangle grid survey pattern used by FIELD (1979) off the Delmarva Peninsula.

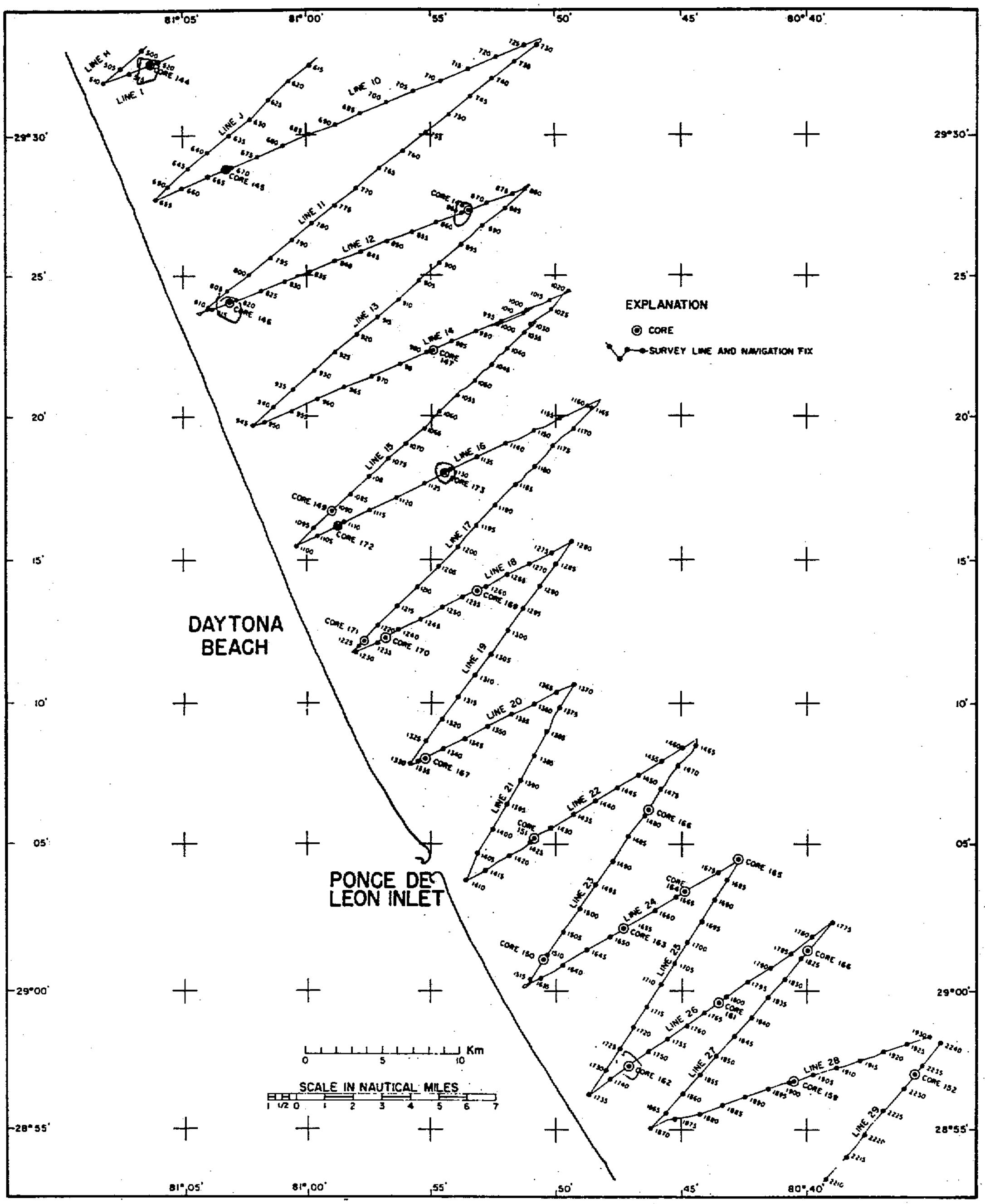

Figure 9. Zigzag reconnaissance survey pattern from the Florida east coast (from MEISBURGER (1990)).

The basic side-scan system consists of three parts:

(1) The transducers, mounted in a hydrodynamically streamlined body (towfish), towed at a depth below the turbulence of the survey vessel's propeller wash
(2) A graphic chart recorder combined with a signal transmitter and processor
(3) A tow cable connecting the two units (Figure 10)

Many modern systems also include a magnetic tape recorder to record the incoming signals, allowing additional signal processing at a later time or enhancing the display of particular features.

Deployed a certain distance above the seafloor, the towfish emits a pulse of acoustic energy. This narrow pulse is transmitted at right angles to the tow direction and reflects from objects on the seafloor. Transducers in the towfish detect the reflections, convert them to electrical energy, and send them to the signal processing unit onboard the survey boat. Even

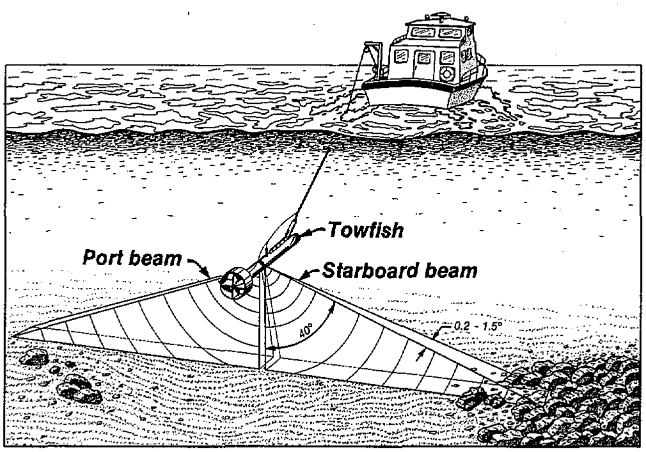

Figure 10. Side-sonar in operation from a small boat.

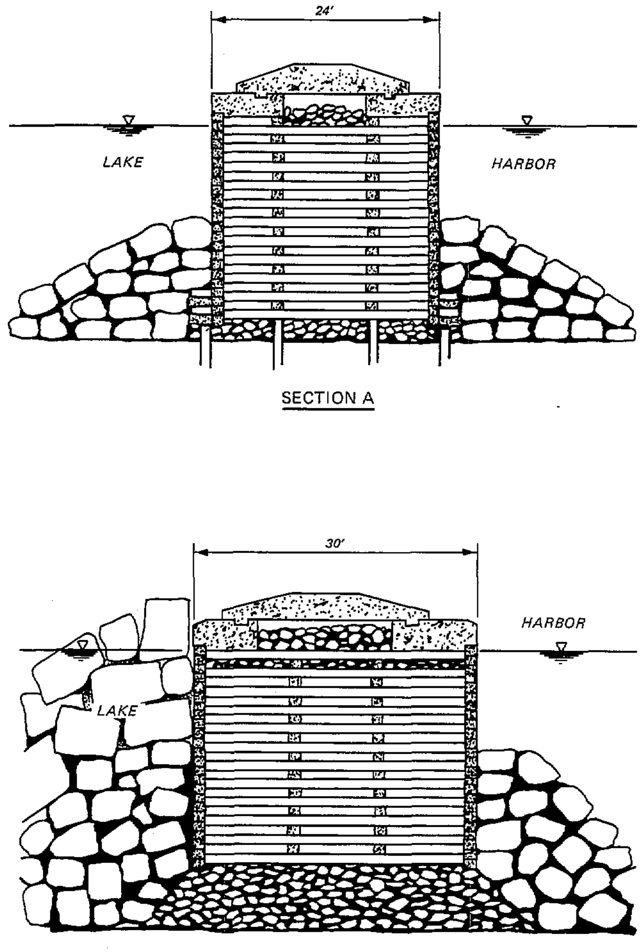

Figure 11. Example of wood crib breakwater with stone riprap toe protection and concrete cap. Breakwaters of this type are common throughout the Great Lakes (from MORANG 1987).

when the signals are recorded on magnetic tape, they are typically also recorded in analog form on paper strip charts as the survey progresses. Each returning signal is plotted on the paper a distance from the center line corresponding to the time it was received. The center line on the paper represents the towfish's trackline. Seafloor objects which are close to the trackline are displayed near the center line, while objects located near the limit of the selected horizontal range are printed at the edges of the record. Objects directly underneath the towfish are normally not imaged because of the geometry of the sonar's beam pattern.

The recorded image is called a *sonograph* and is analogous to a continuous aerial photograph. It can give indications of the nature of the reflecting surface because the stronger the returning signal, the darker the corresponding mark on the paper. The intensity of the reflected signal is a function of material properties as well as of relief. Hard objects such as boulders and steel produce an intense reflection, whereas a flat, soft clay seafloor reflects very little signal. On most side-scan systems, the reflection of an object is recorded as black while the acoustic shadow behind the object is white (the opposite of what we see in a photograph). The printing on some side-scan recorders can be reversed, which makes the image resemble a photograph, but we do not recommend this change because it confuses experienced interpreters who are familiar with the traditional black return/white shadow display. The width of the shadow zone and the position of the object relative to the towfish can be used to calculate an object's height. BELDERSON *et al.* (1972), FLEMMING (1976), LEENHARDT (1974), and MAZEL (1985) provide additional details on the use and theory behind side-scan sonar. In an effort to characterize bottom type, some researchers have been developing relationships between the intensity of backscattered side-scan acoustical energy and the grain size of the bottom materials (*e.g.*, SCHWAB *et al.* (1991) and SCHWAB and RODRIGUEZ (1992)).

Side-Scan Sonar Practical Considerations

The horizontal distance that is imaged can be selected by the operator and, for most commercial side-scan sonars, is between 25 and 500 m. The choice of horizontal range is based on water depth, type of search pattern, size and shape of target, and desired resolution of the image. Usually a range of 25 or 50 m is selected when a detailed image is desired, while a general reconnaissance survey will be run at a range of 100 m or more.

For marine surveys close to shore or in shallow inland waters, lack of water depth severely restricts the horizontal range that can be achieved. A traditional "rule of thumb" is that the fish should be towed at a distance above the seafloor of about 10 percent of the selected horizontal range (FLEMMING, 1976). As an example, in 10 m water, the minimum tow depth will be about 2 m (to keep the fish below waves, surface turbulence, and propeller wash), leaving the fish about 8 m above the seafloor. Therefore, maximum horizontal imaging range will be about 80 m and the recorder scale should be set at 100 m.

Many factors affect image resolution. Vessel speed is one of these: a slow speed enhances resolution because it allows

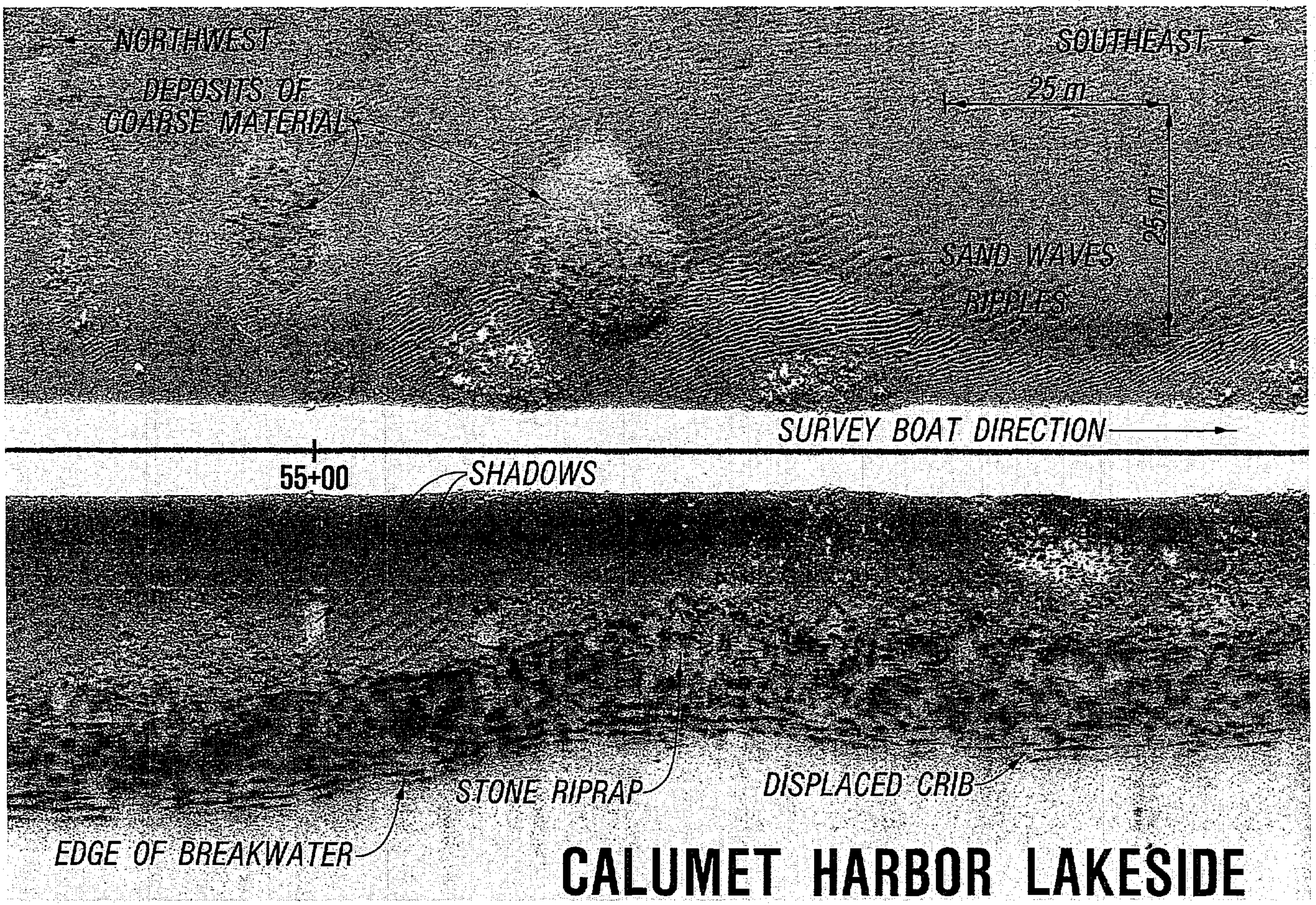

Figure 12. Lakeside, Calumet Harbor breakwater (near Indiana-Illinois border) (from MORANG 1987).

more signals to be transmitted for a given linear distance of seafloor. Typically, survey speed must be kept below 3–4 knots for satisfactory record quality. Wave action also degrades quality. In rough seas, as the boat rocks and rolls, the tow cable is constantly jerked, in turn causing the tow fish to twitch and jerk. Various shock-absorbing mounts using elastic bungee cords can be rigged up to support the cable, but this author has not found these measures to be particularly helpful. In shallow water, when using survey boats up to about 20 m length, 1.0-to-1.25-m waves are about maximum for satisfactory records. In deeper water, the longer tow cable absorbs considerable shock. However, even when using 50-m oil-field workboats on the continental shelf, side-scan record quality severely degrades once waves exceed 2 m. Sometimes, in long-period swell conditions, survey lines can be run with the seas, allowing the engines to be throttled back. However, opposing the seas requires more power, and the extra turbulence and vibration often ruins the records.

Other problems affect deep-water operations. Ringing or strumming can occur when the frequency of the cable matches the motions of the vessel. Bungee cord shock absorbers or plastic streamers (resembling fuzz or hair) can reduce the strumming effect. Sometimes strumming can be eliminated by changing vessel speed or cable layback. Analog side-scan and subbottom signals are often seriously degraded when using tow cables longer than 500 m. The quality and electrical integrity of connectors and cable splices is especially critical when using long tow cables. Newer digital systems may not suffer from signal degradation problems to as great an extent as analog systems.

Planning Side-Scan Sonar Surveys

One of the worst mistakes a researcher can make is to simply contract with a survey company to go to sea and collect side-scan records based on vague criteria of looking for coral reefs, sand ridges, or other geology. Several critical factors, that greatly affect the cost of the project, must be considered before offshore reconnaissance surveys begin:

(1) What is the resolution, or the size of the objects that must be identified? If, for example, a researcher needs to identify 10-m^2 coral outcrops up to several km offshore, the surveys should be rather simple to conduct. If he insists on identifying individual coral heads that are 10×10 cm, it can be accomplished but only at extraordinary cost.

(2) What is the precision of the surveying; *i.e.*, the repeat-

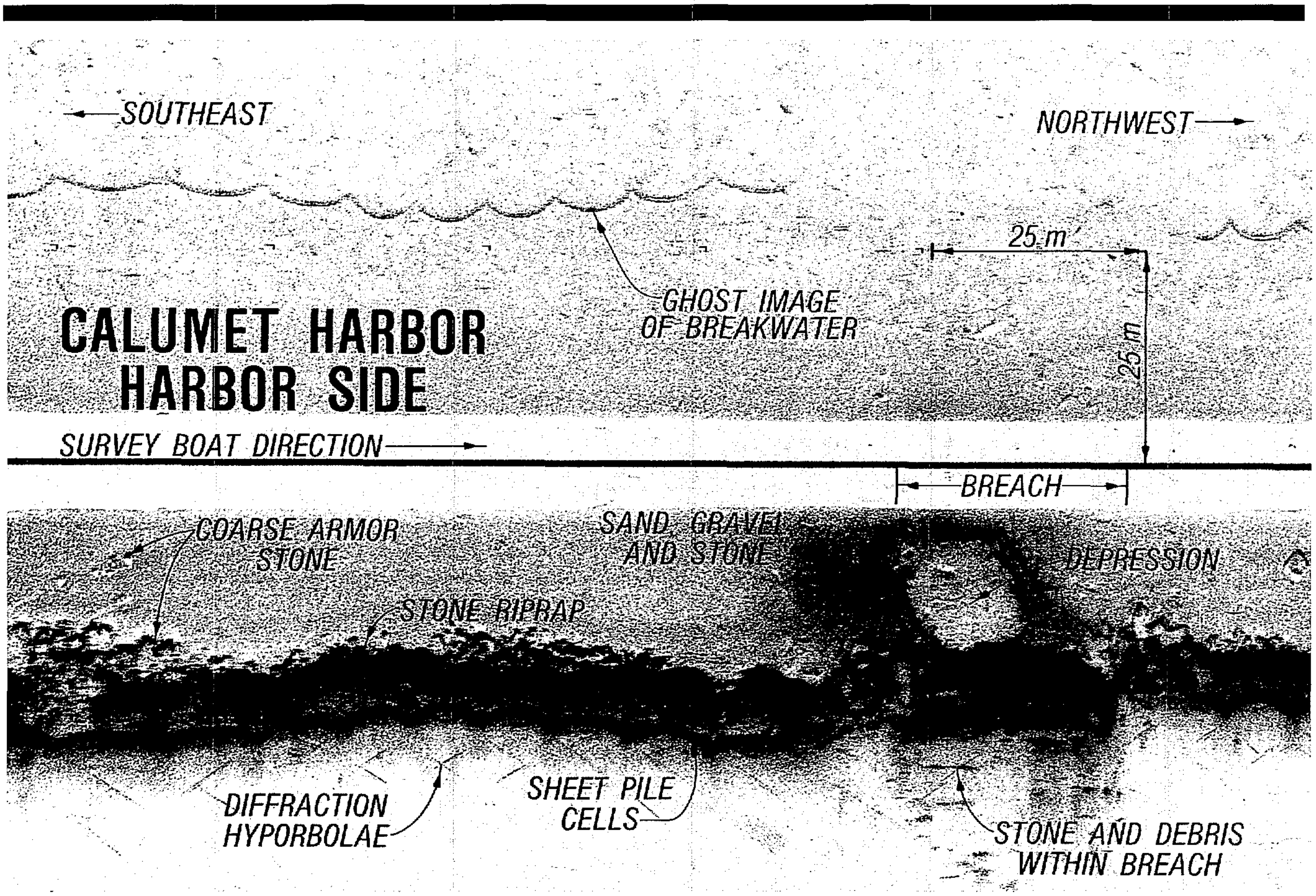

Figure 13. Lakeside, Calumet Harbor breakwater (near Indiana-Illinois border) (from MORANG 1987).

ability of reoccupying a specific site? For a broad area reconnaissance (for example, Corps of Engineers Class 3 specifying two-dimensional one-sigma RMS positional error not to exceed 100 m), surveys can be run at modest cost. If the user needs Class 1 (RMS positional error not to exceed 3 m), costs will be dramatically higher. A potential data user must also consider the issue of how was the survey precision validated? Specifying a standard for a survey is the first step; the contractor has to deliver this quality and document that it was achieved.

(3) When are the surveys to be conducted? The calmer the weather, the better the quality. How much weather downtime can the client afford to pay while the crew waits for optimum seas? Off the Oregon coast, where seas often exceed 2 m, it may be wise to charter as big a boat as can be afforded. In the Gulf of Mexico, smaller and less costly vessels may suffice.

(4) In what form is survey data needed? Most surveys are now recorded digitally so that the tapes can be replayed and reprocessed to make mosaic maps or enhance particular features. But for a broad-area reconnaissance, analog paper records may be sufficient.

(5) WHO WILL INTERPRET AND MAP THE SURVEY DATA! This is far from a trivial matter. In many cases, it is advantageous to have the survey company do the interpretation so that they are faced with correcting navigation errors, cataloging data, and converting datums. All too often, side-scan (and other seismic) records are given to the inhouse "expert" to interpret, but this proves to be false economy considering the time required to sort through the survey logs, prepare base maps, plot features, and prepare a summary or report. As stated earlier, field data should be interpreted immediately, preferably as the survey is in progress so that, if necessary, the program can be adjusted to enhance the records or cover in greater detail unexpected or especially interesting features. We recommend that the principal investigator of a geophysics project be involved in all aspects of the program: planning, field data collection, and interpretation.

(6) Is there a need for a high precision bathymetric survey at the same time? Normally, side-scan sonar and bathymetry surveys should be run simultaneously because one tool complements the other during interpretation. However, conducting bathymetric surveys is an expensive specialty. What precision is needed? As discussed above, a Class 1 survey costs dramatically more than a Class 3 survey.

EXAMPLES OF SIDE-SCAN INTERPRETATION

Many turn-of-the-century breakwaters in the Great Lakes consist of wood frames, known as cribs, that were built on

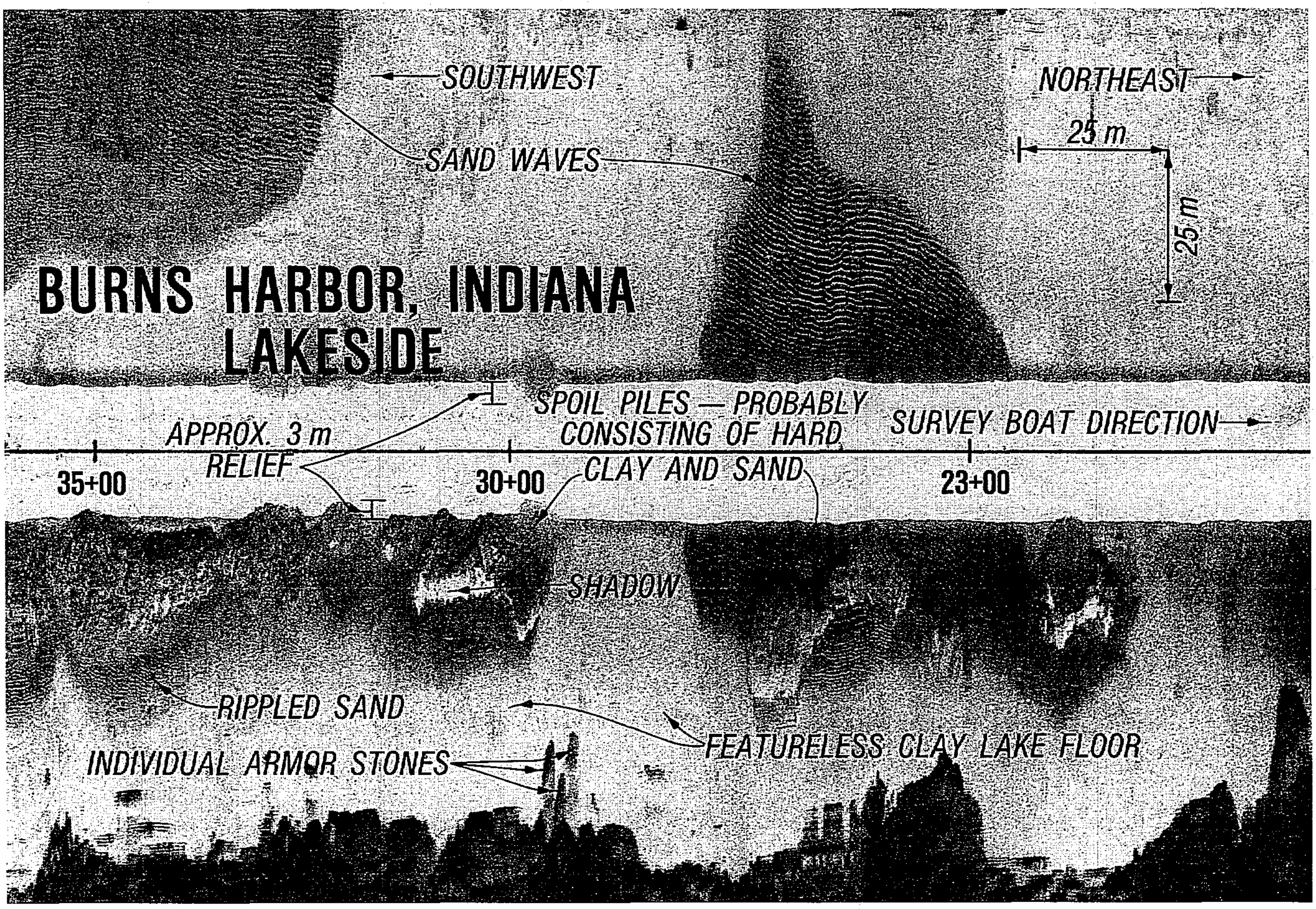

Figure 14. Lakeside, Burns Harbor, Indiana (southeast corner of Lake Michigan).

land by skilled carpenters, floated into place, and filled with stone rubble (Figure 11). In recent years, many of these breakwaters have begun to deteriorate. Figure 12 is a sonograph from Calumet Harbor in southern Lake Michigan. The wooden crib breakwater, protected with stone riprap, is seen in the bottom of the figure. The edge of the breakwater is marked with multiple lines, images of the wood beams. Near the right side of Figure 12, a discontinuity in the lines may represent a displaced crib that has begun to settle or tip. The coarse stone riprap that protects the toe is also evident. Further offshore, several oval deposits of coarse material lie on the lakebed. These may be piles of material dropped in the wrong location during construction or rehabilitation. The mound near the center figure appears to have considerable relief because the side closest to the towfish path (the center line) is dark, representing a strong reflection, whereas the opposite side is in shadow (which recorded as white). Ripples and sand waves can be seen on the lake bottom, indicating the presence of sand.

Another method used to build breakwaters in the Great Lakes was to drive steel sheet pile in the form of large circular cells. These units were filled with rubble and capped with concrete. The lower half of Figure 13 shows the sheet pile cells at Calumet Harbor, protected with stone riprap. In this case, the returns from the vertical steel walls were so intense, the pattern of the cells is better seen on the opposite (upper) side of the sonogram in the form of ghost images. The strong reflections from curved sides of each cell have produced diffraction hyperbolas, similar to the hyperbolas that are created by sharp subsurface reflectors in subbottom geophysical records (for example, from the edges of reefs or rock outcrops). A damaged section of the breakwater shows up as a wide area of rock debris with a depression in the center. The harbor floor in the area is almost featureless and consists of clay with little or no sand. The gains and thresholds on the side-scan system (at least on a manually-adjusted system) must be set so that even a featureless seafloor will produce a slight signal return—this is necessary in order to distinguish places where there is no return, such as from behind objects or in holes.

Rubblemound breakwaters produce dark, irregular, blocky reflections. Figure 14, an example from Burns Harbor, Indiana, shows that the breakwater is built on a clayey lake bed. Thin veneers of sand cover portions of the bed. As at Calumet Harbor, there are piles of unidentified coarse material on the lake bed some distance from the jetty.

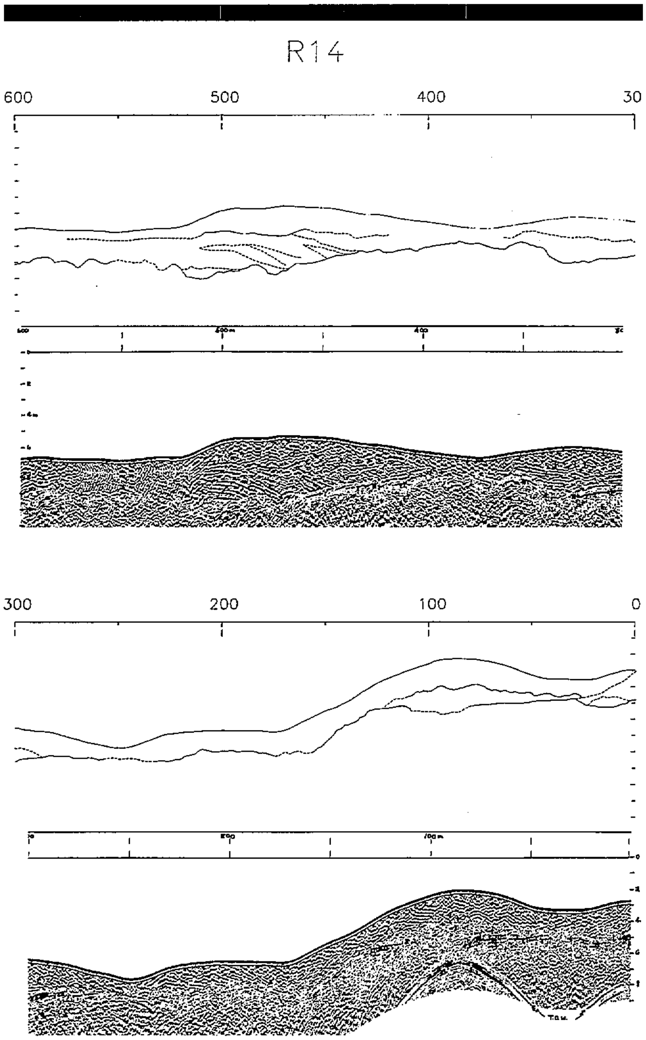

Figure 15. Ground-penetrating radar record from St. Joseph, Michigan (data collected and processed by Western Michigan University).

GROUND-PENETRATING RADAR (GPR)

Background

Commercially-available short-pulse radar equipment used for subbottom imaging consists of a control unit, magnetic tape recorder, and power supply, and a combination transmit and receiving antenna unit. Electromagnetic energy is reflected from earth materials because of variations in dielectric contrast and electrical resistivity. These contrasts differ and may exceed the acoustic anomalies produced by the same materials; therefore GPR can sometimes reveal strata and material changes that might not be revealed by acoustic methods. Radar data interpretation is usually based on the echo delay formula (SELLMANN, DELANEY, and ARCONE, 1992):

$$d = \frac{ct}{2\sqrt{\epsilon}} \tag{6}$$

where:

d = depth of a reflector (cm)
t = echo time delay (ns)
c = speed of electromagnetic waves in a vacuum (30 cm/ns)
ϵ = n^2 (relative dielectric constant); for water, $\epsilon = 81$.

This formula applies to reflections from flat, horizontal interfaces at least several wavelengths long or to scattering from point sources. It can be applied to successive layers if ϵ is known for each layer and the time delays to each layer can be picked off the record.

Signal attenuation is caused by several factors (SELLMANN, DELANEY, and ARCONE, 1992):

- Conductive and dielectric absorption
- Interface transmissions
- Spherical beam spreading

The last factor is compensated by automatic Time Range Gain, which applies an amplitude gain that increases with time of return. ULRIKSEN (1982), DANIELS (1989), and DUVAL (1989) cover in detail fundamentals of GPR and its use in civil engineering and geology. OLHOEFT (1988) provides a bibliography of earlier GPR papers.

Applications of GPR

Using both acoustic profiling equipment and ground-penetrating radar in freshwater surveys permits researchers to obtain more complete subbottom data because the two approaches respond to different physical properties and have different spatial sensitivities (SELLMANN, DELANEY, and ARCONE, 1992). The resolution of GPR is typically less than that of high-resolution acoustic profilers. For example, the pulse from a 50 mHz (center frequency) radar has a duration of about 50 ns, which in water is about 1.7 m long. A 100-mHz commercial radar with pulse duration of 28 ns has a pulse length of about 0.8 m. In comparison, a 7 kHz profiler has a wavelength of about 0.2 m. However, despite the lower resolution, GPR is valuable because it can sometimes image areas that are opaque to acoustic energy (*e.g.*, gas-charged sediments) or do not possess impedance contrasts adequate to produce acoustic signal returns.

For the most part, GPR has not been used in oceanic coastal areas because of subsurface units that cause severe signal attenuation. These typically include fine-grained estuarine and lagoonal clays and coarse-grained units that contain salt water. However, FITZGERALD *et al.* (1992) and VAN HETEREN *et al.* (1994) have successfully used GPR to delineate structure and stratigraphy of beach ridges in New England, and MEYERS *et al.* (1994) have reported similar success on the Pacific Coast. In general, GPR is successful when imaging wide and high barriers where there is a thick lens of freshwater.

Lake Michigan GPR Examples

The following GPR examples are from a Coastal Engineering Research Center monitoring project conducted along the southeast shore of Lake Michigan near the town of St. Joseph, Michigan. One of the purposes of the study was to determine the thickness of the sand layer overlying glacial till.

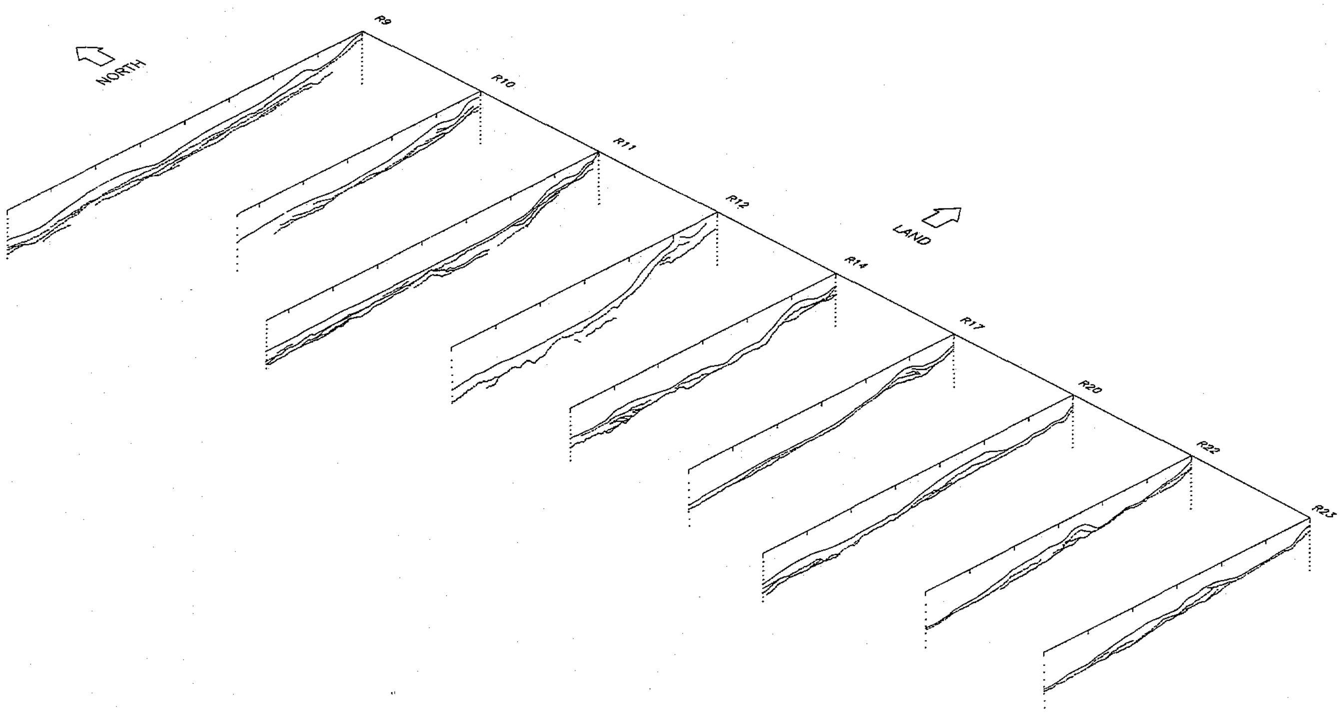

Figure 16. Lakefloor structure off St. Joseph, Michigan, based on parallel GPR lines.

The GPR system in this study, developed by Western Michigan University, used a 145 mHz monostatic dipole antenna mounted on a plastic sled. An acoustic transducer pointed upward to measure water depth as the sled was towed along the lake bottom. By keeping the sled on the bottom, the antenna achieved better coupling with the sediment and reduced the signal attenuation that occurs when an antenna is towed through the water. When the data were processed, the records were corrected to show the correct water depth. In Figure 15, an example of the processed records is compared with an interpreted section, similar to the type of interpretation usually used with acoustic subbottom profiler records. Figure 16 is a diagram showing nine GPR lines from the St. Joseph study.

SUMMARY

Geophysical survey methods are powerful tools for delineating subsurface structure and stratigraphy in coastal areas. But these tools must be used carefully by experienced geophysicists and contractors. Projects must be planned thoroughly to take advantage of the particular instruments being used and the scale and nature of features that are to be identified.

For bathymetric surveys, project planners should ask, as a minimum, the following questions and plan their surveys accordingly:

- What are the boundaries of the survey area and how far offshore will the area extend? This affects navigation and tidal modeling.
- What precision and accuracy is needed (or at least desired)?
- What is the budget for the project? This directly affects whether the requested precision and accuracy can be achieved considering factors such as project location, mobilization costs, distance from harbors and other support facilities, and data processing.
- Who is the customer and how does the customer intend to use the data? This directly affects what type of output is needed (raw digital data, finished maps, etc.).
- How will the project be jeopardized by weather delays?

Subbottom geophysical surveys need to be planned with the above considerations in mind along with additional factors:

- What is the scale (size) of objects that need to be analyzed? What is the minimum resolution that will image the target?
- Who will analyze and interpret the records?
- How will the output be displayed or plotted?
- Is there a significant chance that the survey area is acoustically opaque because of gassy sediments? If so, acoustic geophysical tools may not be suitable. Possibly an alternative method like ground-penetrating radar can be used.

We reiterate that geophysical data must be interpreted immediately, preferably while the survey is underway. This way, mistakes can be corrected and survey parameters can be adjusted if the data is not revealing the structures that are considered important. We must also emphasize that geophysical tools are indirect windows into the world beneath the sea—they provide a model of sediments and strata and structure. The most successful results come from comprehensive studies where the subsurface model is verified with cores or other direct evidence.

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